A method and apparatus for image processing

The present invention relates to methods and apparatus
for image processing and, particularly, though not

5   exclusively, to the processing of Nuclear Magnetic
Resonance image data.

Certain imaging technologies, such as Magnetic Resonance
(MR) imaging, permit the subject of the imaging process

10   to be fully imaged in three spatial dimensions. They
permit the acquisition of image data which is able to
represent a 3D "view" of the subject from any aspect or
perspective in 3D space. This is in contrast to image
data acquired through a series of predetermined

15   "projections" which only enable "views" limited to one of
the predetermined projections employed in acquiring the
image data.

Dynamic imaging, such as dynamic MR imaging, may involve

20   the acquisition of a time-series of image data sets in
which each data set is able to represent an image of the
subject fully in 3D at one of a series of successive
instants (or brief periods) in time. Dynamic imaging is
often used to record the internal changes in properties

25   of a stationary subject which are induced by a controlled
change-inducing influence. An example of this is

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contrast-enhanced medical MR imaging in which a "contrast

agent" is introduced into a stationary subject (e.g. a

person) which is detectable as an increase in the image

contrast/brightness of those internal parts of the

5   subject in which the agent is located.

An analysis of the change in image properties (e.g. in

image contrast/brightness), over time, of chosen fixed

points or static regions within the imaged volume of the

10   subject enables an assessment of the properties of the

chosen fixed points/regions within that imaged volume.

However, this assessment is rendered void if the chosen

fixed points/regions of the imaged subject are assumed to

be fixed/static but were, in fact, not static during the

15   time-sequence in question. The result would be that

changes in the properties of chosen points/regions would

not be due to changes in the properties of the same

point/region of the subject, but would instead be due to

the chosen point/region not representing the same

20   point/region of the image subject for the duration of the

time-sequence. Thus, image changes would be due to

changes in the position of the subject (i.e. subject

motion) rather than to changes in the subject per se.

25   For example, the image analysis procedure in breast

dynamic imaging typically involves localisation of a

lesion within an image of the subject containing a contrast agent. Image analysis may involve analysis of the shape of "time-intensity" curves representing the temporal development of pixel intensity of chosen

5   points/regions of the subject image and may involve pharmacokinetic modelling. All the techniques assume that the imaged volumes within the time-series are properly spatially aligned. A dynamic breast scan is a time consuming examination. The overall examination time can

10   be up to 30 minutes. During such a long time a patient can move because of discomfort or tension. The motion most likely damages the spatial alignment of the imaged subject volumes within the time-sequence, and may lead to unreliable results, such as appearance of false lesions

15   within the subtracted post-contrast image. Also, no reliable analysis based on the time-intensity uptake curves is possible if the curves are not representative of the same point/region of the imaged subject. The motion of breast is not always easy to detect. Due to

20   the high degree of elasticity of a breast tissue, a local motion may occur resulting in local deformation of some region the breast and tiny deformation of the remaining part of the volume. It follows that it is important to be able to assess a quality of alignment of image data, in

25   the local region of interest, as between imaged volumes within a time-sequence.

The present invention aims to overcome at least some of the above deficiencies of the prior art.

5   The present invention proposes to provide a method and/or apparatus enabling one to determine if a contrast/intensity change of a chosen point within an imaged subject volume (e.g. a lesion) is a motion artefact. An apparatus and method for fast visual

10   assessment of the imaged subject volume's alignment quality (within the time-sequence) is provided, and interactive display tool enabling effective use of this method is provided.

15   In a first of its aspects, the present invention may provide a method of processing a time-sequence of separate image data sets each set comprising a plurality of image data items which each represent the location of an image pixel of the image subject according to a

20   spatially fixed reference frame within which the subject is located, the method including the steps of:

   (a) selecting a plurality of separate image pixel locations within the reference frame;

   (b) selecting from each of a plurality of the

separate image data sets those image data items which

represent image pixels located at the plurality of

separate image pixel locations;

(c) generating a time-domain image according to the

5   selected image data items wherein those image pixels of

the time-domain image sharing a common image pixel

location within the reference frame are arranged in time-

sequence in a line containing only those pixels.

10   Thus, the reference frame within which the subject is

located is common to all image data items of all image

data sets of the time-sequence. By lining-up image

pixels sharing the same spatial coordinates within the

reference frame, one lines-up the temporally successive

15   pixel representations of the same point of space (imaged

at successive times within a time-sequence) within the

reference frame in which the subject is located. In

doing so, one does not necessarily line-up image pixels

of the same points of the imaged subject since the

20   subject (or a part of it) may have moved its location

within the reference frame during time-sequence.

However, should such subject movement occur, a

consequence is often a visibly discontinuous change, or

an irregularity, in a property of image pixels (e.g.

25   brightness, or colour) as between neighbouring pixels of

the line of pixels in the time-domain image. The

location of such a discontinuity/irregularity within the

time-domain image identifies two image volumes within the

time-sequence between which the subject motion occurred.

This method may be applied to image data sets with image

5   data items representing pixel locations extending only in

2D (e.g. image "slices"), as well as those extending in

all three spatial dimensions (i.e. image volumes).

Preferably, each image pixel is an image voxel such that

10 each image data item represents the location of an image

voxel of the image subject according to a spatially fixed

three-dimensional reference frame, preferably, each image

data set contains image data items representing image

voxel locations spanning all three dimensions of the

15 reference frame.

By selecting the image data items representing a

plurality of separate image pixel locations within the

reference frame, a time-domain image comprising a

20 plurality of separate lines each containing only those

pixels sharing a common image pixel location may be

provided. The plurality of such separate lines are

preferably arranged side-by-side such that those image

pixels of neighbouring lines which share a common image

25 data set are also aligned so as to form a line. This

arrangement assists in visually assessing image data for

the presence of motion artefacts since such artefacts are

most likely to affect a plurality of image pixel

locations within the reference frame rather than just one

such location. Accordingly, local image features may

5   well display motion artefacts as a collective

discontinuity or irregularity shared by several or each

of the side-by-side lines within the time-domain image.

The time-domain image is preferably generated such that

10   those image pixels of the time-domain image which are

represented by image data items selected from a common

image data set are arranged in a line containing only

those pixels.

15   Often small regions within the imaged subject volume

suffer motion artefacts while the remaining volume does

not. In order to facilitate easy visual identification

of such localised motion, the plurality of separate image

pixel locations selected from within the reference frame

20   at step (a) are neighbouring such locations.

Consequently, provided that localised motion affects a

small region of spatial dimensions matching or exceeding

the spatial separation between such neighbouring image

pixel locations, then motion artefacts will appear in the

25   time-domain image (generated at step (c)) as a collective

discontinuity/irregularity affecting the same regions of

neighbouring of the side-by-side lines therein. Such

collective discontinuity not only indicates the extent of

subject motion but is also easier to spot within a time-

domain image.

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The time-domain image preferably comprises a matrix of

pixels arranged to define columns and rows, wherein each

column (or, alternatively, each row) contains only those

image pixels sharing a common pixel location within the

10   reference frame, and each row (or, alternatively, each

column) contains only those image pixels selected from a

common image data set.

Preferably, the time-domain image is generated such that

15   each separate line of image pixels of a common image

pixel location contains successive line segments

containing only those pixels which share a common image

data set. Thus, each such line segment is comprised only

of several copies of the same image pixel. Each segment

20   within a line may contain the same number of image pixels

(copies) thereby rendering each line segment the same

length. Motion artefacts in a single image pixel

location result in a visible shift of an entire line

segment. This is much easier to identify than is a shift

25   in a single pixel. More preferably, each of the side-by-

side lines of the time-domain image comprises successive

such line segments, and preferably corresponding line

segments of each such side-by-side line are equal in

length (i.e. the same number of image pixels therein).

5   Preferably, the selection of the plurality of image pixel

locations at step (a) comprises selecting a target image

pixel location within the reference frame and

subsequently selecting all image pixel locations which

are intersected by a predefined first locus intersecting

10   the target image pixel location. The locus may be any

predefined shape and may be defined by a mathematical

expression in terms of the coordinates of the reference

frame, or may simply be a preselected trail of successive

image pixel locations extending through the reference

15   frame.

Preferably, the predefined first locus is a line

extending through the reference frame. The line

preferably extends through only one dimension of the

20   reference frame and intersects all pixel locations within

a column or a row of pixel locations within the reference

frame. In this way a linear cross-sectional view (in one

dimension, i.e. 1D) through the imaged subject volume is

provided.

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For example, method may include: selecting a target one

of the plurality of separate image data sets and

selecting therefrom those image data items which

represent image pixels located in a common first plane

5   containing the first locus; and generating a first

spatial-domain image according to the data items so

selected. The method preferably also includes generating

a composite image containing the first spatial-domain

image and the time-domain image aligned such that those

10   pixels of the first spatial-domain image and of the time-

domain image which share a common image pixel location

within the reference frame are arranged in-line.

Such in-line arrangement enables a view of a spatial

15   cross-section of the imaged subject volume and a

simultaneous view of a time-domain image of the subject,

each view sharing at least one common spatial dimension

defined by the first locus. The time-domain image also

extends in the time dimension while the first spatial-

20   domain image extends in two spatial dimensions. In-line

arrangement of the two images enables a direct visual

comparison of the image features present along the common

spatial dimension shared by the two images.

25   Preferably the first locus is simultaneously visually

presented within the composite image as a first locus

image overlaying one or each of the spatial-domain and

the time-domain images and intersecting those image

pixels of the respective images which represent pixel

locations within the reference frame intersected by the

5   first locus. Alternatively, such image pixels may be

highlighted or otherwise rendered distinct from their

neighbouring image pixels within the composite image.

Preferably, the selection of the plurality of image pixel

10   locations at step (a) comprises selecting the target

image pixel location within the reference frame and

subsequently selecting all image pixel locations which

are intersected by a predefined second locus intersecting

the first locus at the target image pixel location. The

15   second locus may be any predefined shape and may be

defined by a mathematical expression in terms of the

coordinates of the reference frame, or may simply be a

preselected trail of successive image pixel locations

extending through the reference frame.

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Consequently, the composite image may contain a second

time-domain image generated according to any one of the

method steps discussed above in respect of the second

predefined locus which intersects the first locus. The

25   second locus is preferably substantially coplanar with

the first locus. The first spatial-domain image and the

second time-domain image are preferably aligned such that
those pixels of the first spatial-domain image and of the
second time-domain image which share a common image pixel
location within the reference frame are arranged in-line.

5   Preferably, a second locus image of the form of the first
locus image may simultaneously be presented in either or
each of the spatial-domain image and the second time-
domain image.

10 The first predefined locus is preferably a line and the
second predefined locus is preferably also a line
substantially perpendicular to the first predefined
locus. This provides a cross-hair effect in a locus
image comprising the first and second locus images. The

15 cross-hairs will centre upon the target pixel location
within the spatial-domain image.

For example, when the first and second locus' are
perpendicular and coplanar the composite image,

20 comprising the first spatial-domain image and both the
first and second time-domain images, provides a composite
image representing three dimensions in which each time-
domain image shares a separate one of the two spatial
dimensions of the first spatial-domain image, and in

25 which each time-domain image extends in the time
dimension. Graphically, the time dimension of each time-

domain image may extend perpendicularly to the spatial

dimension of the image in question. A further spatial

dimension orthogonal to those represented in the first

spatial-domain image may also be represented within the

5   composite image thereby rendering the latter

representative of four dimensions (i.e. three spatial and

one temporal).

Thus, preferably, the selection of the plurality of image

10   pixel locations at step (a) comprises selecting the

target image pixel location within the reference frame

and subsequently selecting all image pixel locations

which are intersected by a predefined third locus

intersecting the first locus and the second locus at the

15   target image pixel location. The third locus may be any

predefined shape and may be defined by a mathematical

expression in terms of the coordinates of the reference

frame, or may simply be a preselected trail of successive

image pixel locations extending through the reference

20   frame.

Consequently, the composite image may contain a third

time-domain image generated according to any one of the

method steps discussed above in respect of the third

25   predefined locus which intersects the first and second

locus'. The third locus is preferably non-coplanar (e.g.

perpendicular) with the first locus and the second locus.

The method may further include: selecting from the target

5   one of the plurality of separate image data sets those

data items which represent image pixels located in a

common second plane being non-parallel and non-coplanar

with the first plane and containing the first locus;

generating a second spatial domain image according to the

10   data items so selected. The method preferably further

includes generating the composite image so as to contain

the second spatial-domain image aligned such that those

pixels of the second spatial-domain image and of the

time-domain image which share a common pixel location

15   within the reference frame are arranged in-line.

In this way, a third spatial domain is represented within

the composite image by the presence of the second

spatial-domain image which also shares one common spatial

20   dimension with both the first spatial-domain image and

the first time-domain image. This common spatial

dimension is defined by the first locus and preferably

the common spatial axis of each of the first time-domain,

first spatial-domain and second spatial-domain images are

25   aligned in parallel and side-by-side such that the time

axis of the first time-domain image and the spatial axes

of the first and second spatial-domain images which are

perpendicular to the first locus, are all aligned

sequentially in-line and in parallel. This permits rapid

visual assessment of image data in three spatial and one

5   temporal dimension.

The method may also include: selecting from the target

one of the plurality of separate image data sets those

data items which represent image pixels located in a

10   common third plane being non-parallel and non-coplanar

with the first plane (and the second plane, preferably)

and containing the second locus; and generating a third

spatial domain image according to the data items so

selected. Preferably the method further includes

15   generating the composite image so as to contain the third

spatial-domain image aligned such that those pixels of

the third spatial-domain image and of the second time-

domain image which share a common pixel location within

the reference frame are arranged in-line. Again, most

20   preferably the parallel alignment of common spatial axes

is provided in a side-by-side arrangement as discussed

above.

The first, second and third planes are preferably all

25   mutually substantially perpendicular. Preferably, the

second plane and the third plane, in respect of which the

second and third spatial-domain images are generated,

each contain the third locus.

The third time-domain image and either the third or the

5   second spatial-domain image are preferably aligned such

that those pixels of the third time-domain image and of

either the second or the third spatial-domain image which

share a common image pixel location within the reference

frame are arranged in-line. The spatial axis of the

10 third time-domain image may be arranged parallel and in-

line with the spatial axis of the first time-domain image

(i.e. the two images side-by-side) when the third time-

domain image is aligned with the third spatial-domain

image. Alternatively, the spatial axis of the third time-

15 domain image may be arranged parallel and in-line with

the spatial axis of the second time-domain image (i.e.

the two images side-by-side) when the third time-domain

image is aligned with the second spatial-domain image.

Preferably, a third locus image of the form of the first

20 or second locus image may simultaneously be presented in

either or each of the second or third spatial-domain

image and the third time-domain image.

Preferably, all image pixels within each of the images

25 contained within the composite image which are

intersected by a locus are highlighted so as to render

them distinguishable from their neighbouring image

pixels, or are overlaid by a locus image which represents

the position of a locus within an image.

5   Planes are non-parallel if the normal extending from one

plane is not parallel to the normal extending from

another "non-parallel" plane.

In a second of its aspects the present invention may

10   provide apparatus for processing a time-sequence of

separate image data sets each set comprising a plurality

of image data items which each represent the location of

an image pixel of the image subject according to a

spatially fixed reference frame within which the subject

15   is located, the method including the steps of:

(a) first selection means selecting a plurality of

separate image pixel locations within the reference

frame;

(b) second selection means for selecting from each

20   of a plurality of the separate image data sets those

image data items which represent image pixels located at

the plurality of separate image pixel locations;

(c) image generating means for generating a time-

domain image according to the selected image data items

25   wherein those image pixels of the time-domain image

sharing a common image pixel location within the

reference frame are arranged in the time-sequence in a

line containing only those pixels.

Each image pixel is preferably an image voxel such that

5   each image data item represent the location of an image

voxel of the image subject according to a spatially fixed

three-dimensional reference frame. Preferably each image

data set contains image data items representing image

voxel locations spanning all three dimensions of the

10   reference frame.

The first selection means is preferably arranged to

select a target image pixel location within the reference

frame, and includes locus means for defining a first

15   locus intersecting the target image pixel location,

wherein the first selection means is arranged to select

all image pixel locations which are intersected by the

first locus.

20   The first locus is preferably a line extending through

the reference frame. The line preferably extends through

only one dimension of the reference frame and intersects

all pixel locations within a column or a row of pixel

locations within the reference frame.

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The image generating means is preferably arranged to

generate the time-domain image such that those image

pixels of the time-domain image which are represented by

image data items selected from a common image data set

5   are arranged in a line containing only those pixels.

The image generating means is preferably arranged to

generate the time-domain image comprising a matrix of

pixels arranged to define columns and rows, wherein each

10   column (or, alternatively, each row) contains only those

image pixels sharing a common pixel location within the

reference frame, and each row (or, alternatively, each

column) contains only those image pixels selected from a

common image data set.

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Preferably the second selection means is arranged to

select from a target one of the plurality of separate

image data sets those image data items which represent

image pixels located in a common first plane containing

20   the first locus; wherein the image generating means is

arranged to generate a first spatial-domain image

according to the data items so selected. Preferably the

image generating means is further arranged to generate a

composite image containing the first spatial-domain image

25   and the time-domain image aligned such that those pixels

of the first spatial-domain image and of the time-domain

image which share a common image pixel location within the reference frame are arranged in-line.

The locus means is preferably arranged to define a second

5   locus which intersects the first locus at the target image pixel location and is preferably substantially coplanar with the first locus. The second selection means is preferably arranged to select all image data items the pixel locations of which are intersected by the second

10   locus. The image generation means is preferably arranged to generate a second time-domain image in respect of image data items so selected. Preferably the image generating means is further arranged to generate a composite image which contains a second time-domain image

15   in which the first spatial-domain image and the second time-domain image are aligned such that those pixels of the first spatial-domain image and of the second time-domain image which share a common image pixel location within the reference frame are arranged in-line.

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The locus means is preferably arranged to define the first locus as a line and the second locus is a line substantially perpendicular to the first locus.

25   The locus means is preferably arranged to define a third locus which intersects the first locus and the second

locus at the target image pixel location and is contained

within one of the second plane and the third planes. The

second selection means is preferably arranged to select

all image data items the pixel locations of which are

5   intersected by the third locus. The image generation

means is preferably arranged to generate a third time-

domain image according to image data items so selected.

Preferably the image generating means is further arranged

to generate a composite image

10   which contains the third time-domain image, wherein the

third time-domain image and one of the second and the

third spatial-domain images respectively are aligned such

that those pixels of the third time-domain image and

those pixels of the one of the second and the third

15   spatial-domain images which share a common image pixel

location within the reference frame are arranged in-line.

The second selection means is preferably arranged to

select from the target one of the plurality of separate

20   image data sets those data items which represent image

pixels located in a common second plane being non-

parallel and non-coplanar with the first plane and

containing the first locus; the image generating means is

preferably arranged to generate a second spatial-domain

25   image according to the data items so selected.

Preferably the image generating means is also arranged to

generate the composite image so as to contain the second

spatial-domain image aligned such that those pixels of

the second spatial-domain image and of the time-domain

image which share a common pixel location within the

5   reference frame are arranged in-line.

The second selection means is preferably arranged to

select from the target one of the plurality of separate

image data sets those data items which represent image

10   pixels located in a common third plane being non-parallel

and non-coplanar with the first plane (and preferably the

second plane) and containing the second locus; and the

image generating means is preferably arranged to generate

a third spatial domain image according to the data items

15   so selected.   Preferably the image generating means is

also arranged to generate the composite image so as to

contain the third spatial-domain image aligned such that

those pixels of the third spatial-domain image and of the

second time-domain image which share a common pixel

20   location within the reference frame are arranged in-line.

The image generating means is preferably operable to

generate a composite image in which the spatial axis of

the third time-domain image may be arranged parallel and

25   in-line with the spatial axis of the first time-domain

image (i.e. the two images side-by-side) when the third

time-domain image is aligned with the third spatial-

domain image. Alternatively, the spatial axis of the

third time-domain image may be arranged parallel and in-

line with the spatial axis of the second time-domain

5   image (i.e. the two images side-by-side) when the third

time-domain image is aligned with the second spatial-

domain image. Preferably, the locus means is operable to

define a third locus image of the form of the first or

second locus image and to simultaneously present the

10   third locus image in either or each of the second or

third spatial-domain image and the third time-domain

image.

The second selection means is preferably arranged to

15   select the first, second and third planes to be mutually

substantially perpendicular.

A plurality of items are "in-line" if they are all

arranged in/along a common single straight line.

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The invention may also comprise computer means programmed

to perform the method according to the invention is its

second aspect including some, none or all of the

preferred features or variants discussed above.

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In a third of its aspects, the present invention may provide computer means programmed to perform the method according to the invention in its first aspect, including none or all of the preferred features or variants

5   discussed above.

In a fourth of its aspects, the present invention may provide a computer program product containing a computer program for performing the method according to

10   the invention in its first aspect, including none or all of the preferred features or variants discussed above.

The present invention may also provide a computer program containing computer code which, when implemented,

15   performs the method according to the invention in its first aspect, including none or all of the preferred features or variants discussed above.

The present invention may also provide an image generated

20   according to the invention in its first aspect, including none or all of the preferred features or variants discussed above.

The invention shall now be described in terms of the

25   following non-limiting examples with reference to the accompanying drawings in which:

Fig. 1 illustrates a plurality (a) to (i) of time-domain images displaying various degrees of image discontinuity/irregularity due to subject motion (i.e. motion artefacts);

5   Fig. 2 illustrates two time-domain images (a) and (b) displaying the temporal development of contrast agent uptake within an imaged subject at selected regions thereof;

Fig. 3 illustrates a composite image comprising

10   three time-domain images and three spatial-domain images defined by three perpendicular locus';

Fig. 4 illustrates schematically a reference frame within which a subject is located and according to which the image data items of the imaged subject represent the

15   locations of image voxels representing points within the space defined by the reference frame;

Fig. 5 illustrates schematically a motion artefact within a time-domain image generated according to a predefined locus L;

20   Fig. 6 presents a general view of a 4D orthogonal display tool;

Fig. 7 illustrates a composite image comprising two time-domain linogram images and a single spatial-domain image associated therewith.

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Referring to Fig. 4 there is illustrated a reference

frame R comprising three orthogonal axes (x, y, z)

defining a spatially fixed coordinate system within which

is located a subject O in respect of which image data

5   items fully representing the object in 3D have been

acquired. The acquired 3D image data items each

represent the location of an image voxel of the image

subject O according to the spatially fixed reference

frame R within which the subject is located. A data set

10   comprising a plurality of such image data items

accordingly represents a plurality of locations within

the reference frame R spanning a predefined volume of

space V. A given such data set is acquired over a

predetermined brief period of time sufficient to acquire

15   all of the image data items comprising the set.

Acquisition of such image data sets may be repeated a

predetermined number of times (e.g. M times) thereby

defining a time-sequence of separate image data sets each

representing the same fixed volume V at the same fixed

20   image voxel locations within the reference frame R.

Given such a time-sequence or series of M dynamic data

sets (volumes), each imaged volume defined by a given

data set within the sequence is represented as a stack of

25   frames with each frame comprised of a 2D lattice of image

voxels. The resulting image volume comprises a lattice

of image voxels having dimensions $N_x \times N_y \times N_z$ (respectively

number of columns and rows in a frame, and a stack

length).

5   The method includes the initial step of selecting a

plurality of separate image voxel locations within the

reference frame (R) by: selecting a target voxel from the

volume lattice V (hereinafter referred to as the "seed

voxel"); selecting from the volume V a frame (P)

10 containing the seed voxel; and, from the selected frame

selecting the row (L) containing the seed voxel. The

selected row represents a predetermined linear locus with

which to select image voxel locations (once the seed

voxel is identified). The locus need not be linear.

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By selecting from each of the M separate image data sets

those image data items which represent image voxels

located at the plurality of selected image voxel

locations defined by the locus L, one obtains image data

20 items for use in generating a time-domain image. This

data selection step may occur subsequent to selection of

the image voxels locations via locus L, or may occur in

tandem by, for example, after selecting a seed voxel,

subsequently selecting from each of the M data sets the

25 image data items contained in the selected frame (P), and

then selecting image data items intersected by the locus

L within each selected frame of data.

The process of selecting voxel locations may be

5   undertaken with a computer and visual display unit

implementing software according to the invention enabling

a seed voxel (S), a frame (P) and a row or other locus

(L) to be selected interactively from a visual display of

an image or images of the object derived from one, some

10   or all of the M image data sets.

Subsequent to data selection, a time-domain image is

generated from the selected image data items wherein

those image voxels of the time-domain image sharing a

15   common image voxel location within the reference frame

are arranged according to the time-sequence in a line

containing only those voxels.

This may be done by combining the selected rows (R) into

20   an image where order of rows follows the order of

acquisition of the M data sets (volumes) from which the

rows of data were selected. The resulting time-domain

image has dimensions $N_x \times M$.

25   Any point on the time-domain image corresponds to a point

in the reference frame R as represented by an image data

set representing the volume V. Given the coordinates of the seed voxel S are (x_S, y_S, z_S), the points $P_{TD}(u,v)$ within the volume V which are represented by the time-domain image corresponds to the four-dimensional points in the

5   original data:

$$P_{4D}(x, y, z, t) = P_{4D}(u, y_S, z_S, v) \qquad\qquad (1)$$

Where x, y, z are volume lattice coordinates in the

10   reference frame R, and the fourth coordinate, t, is a temporal coordinate, i.e. index of the dynamic volume within the time-sequence.

Using the same principle, one may create a time-domain

15   image selecting columns L2 passing through the seed voxel S instead of the rows L. That is to say, the locus according to which image voxel locations are selected may be a column L2 rather than (or in addition to) a row L. In such a case the points of interest represented by the

20   time-domain image will be defined by:

$$P_{4D}(x, y, z, t) = P_{4D}(x_S, v, z_S, u) \qquad\qquad (2)$$

Furthermore, one may create a time-domain image selecting

25   a "depth" column L3 passing through the seed voxel S

perpendicular to the row L and column L2. That is to say,

the locus according to which image voxel locations are

selected may be a column L3 rather (or in addition to)

than a row L, or column L2. In such a case the points of

5   interest represented by the time-domain image will be

defined by:

$$P_{4D}(x,y,z,t) = P_{4D}(x_S, y_s, u, v) \qquad\qquad (3)$$

10   This equation assumes that pixels selected from a common

data set are in rows. The choice of image plane from

which this third locus L3 is selected may be the plane

parallel to the plane containing the z axis and the x

axis of the reference frame R, or may be the plane

15   perpendicular to that and containing the z axis and the y

axis of the reference frame.

Figure 5 schematically illustrates a motion artefact

within a time-domain image generated according to a

20   predefined locus L. The time-domain image comprises a

plurality of separate vertical lines 1,2 and 3 etc.

(image columns) each containing only those voxels sharing

a common image voxel location. The plurality of such

separate vertical lines are arranged side-by-side such

25   that those image voxels sharing a common image data set

aligned so as to form a horizontal line (image rows).

This arrangement assists in visually assessing image data

for the presence of motion artefacts since such artefacts

are most likely to affect a plurality of image voxel

5   locations within the reference frame rather than just one

such location. Accordingly, local image features may

well display motion artefacts as a collective

discontinuity or irregularity shared by several or each

of the side-by-side vertical lines 1, 2, 3 etc. (image

10   columns) within the time-domain image.

The time-domain image of Figure 5 is generated such that

those image voxels of the time-domain image which are

represented by image data items selected from a common

15   image data set (e.g. set number m or set number m+1

within the time-sequence of M sets) are arranged in image

rows containing only those voxels. Consequently, the

time-domain image comprises a matrix of voxels arranged

to define columns and rows, wherein each column contains

20   only those image voxels sharing a common voxel location

within the reference frame R, and each row contains only

those image voxels selected from a common image data set

(e.g. set number m).

25   In order to facilitate easy visual identification of

localised subject motion, the plurality of separate image

voxel locations selected from within the reference frame

R are neighbouring such locations. Consequently,

provided that localised motion affects a small region of

spatial dimensions matching or exceeding the spatial

5   separation between such neighbouring image voxel

locations, then motion artefacts will appear in the time-

domain image as a collective discontinuity/irregularity

affecting the same regions of neighbouring image columns

1, 2 and 3 etc. Such collective discontinuity not only

10   indicates the extent of subject motion but is also easier

to spot within a time-domain image.

Each separate image column 1,2,3 etc. of voxels contains

successive column segments (e.g. segment 1A and segment

1B of column 1) containing only those voxels which share

15   a common image data set. Each such line segment is

comprised only of 3 copies of the same image voxel (any

number of copies could be used in practice). Motion

artefacts in a single image voxel location result in a

visible shift of an entire line segment. This is much

20   easier to identify than is a shift in a single voxel.

Thus, while segment 1A of image column 1, derived from

the data set number m displays an image feature

represented by triangles in Figure 5, segment 1b of image

column 1, derived from the data set number m+1 displays

25   an image feature represented by circles. However, the

segment of column 2 associated with set m also displays

an image feature represented by circles. This indicates
that, in between acquiring image data set m and set m+1,
the object feature responsible for the image feature
represented by circles has moved by an amount equal to
5   the separation between the image voxel locations
represented by columns 1 and 2 of the time-domain image.
Thus, the visible discontinuity in columns 1 and 2 (and
3) of the time-domain image is a motion artefact and not
a property of the object per se.

10

Figures 1(a) to 1(i) illustrate a series of time-domain
images of a breast imaged according to the present
invention with data acquired using MR. Figure 1 shows 9
separate examples (Figs.1(a) to 1(i)) of horizontal time-
15   domain images each for a time-sequence comprising seven
separate breast measurements (i.e. M=7). The dynamic
series is derived from seven image volumes: two pre- and
five post-contrast, i.e. image data acquisition performed
before (twice) and after (5 times) administration of the
20   contrast agent Gd-DTPA. The time interval between
acquisition of successive data sets was 90 sec. The data
sets were acquired using 3D T1-weighted fast spoiled
gradient echo sequence. For better visual representation
the columns of the time-domain images generated with
25   column segments each containing two identical image
voxels (see figure 5 and the discussion thereof).

Looking at the examples, one can easily conclude that cases (a-c) show no motion, in cases (d-g) motion is obvious, and cases (h, i) present local motion (circled

5   on the images).

The time-domain imaging approach may be used for 4-Dimensional visualisation of contrast enhancement of a subject containing a contrast agent. This application of

10   the time-domain image preferably employs "subtracted" images in which the voxel value of each "subtracted" image data item represents the difference in voxel intensity (i.e. the contrast) as between the same voxel position in two different images, the first image being

15   of the subject containing no contract agent and the second image being of the subject after administration of a contrast agent. In this case a time-domain image created for a seed voxel S selected inside a lesion on one a subtracted image will show the temporal pattern of

20   contrast enhancement.

Figure 2 shows fragments of horizontal time-domain MR breast images. The images display two lesions (Fig.2(a) and Fig.2(b)) with different patterns of voxel

25   enhancement. In both case the seed voxel (S) was selected near the centre of a lesion. The time axis is oriented

from top to the bottom of the images. This means that the
top row of each image was selected from the first post-
contrast image data set, the next one from the second,
and so on. One can see in the figure 2(a) that the

5   central part of the lesion is not enhanced on the first
image (top line of figure 2(a) - indicated by arrow), but
becomes enhanced at the bottom of the image (i.e. at a
later time within the time-sequence). At the same time,
the peripheral region on the lesion is enhanced at the

10   top of the image of figure 2(a). The figure 2(b) presents
opposite behaviour when maximum of the lesion central
region enhancement is at the top, and maximum of the
periphery enhancement is at the bottom, when the contrast
is already washed out from the centre (pointed to by an

15   arrow in fig.2(b)).

Time-domain images may be generated which represent the
time-development of image voxels intersected by
perpendicular linear locus' lying within the same

20   selected frame/plane (P). For example the time-domain
image derived from the row locus (L) may represent the
horizontal dimension of the volume V, while the image
derived from the column locus (L2) represents the
vertical dimension. A third complimentary time-domain

25   image may be created using similar approach according to
a third locus L3 extending through the seed voxel S in a

36

direction orthogonal to the frame/plane (P), and would

represent the depth dimension.

Equations 1, 2 and 3 imply a way of 4D navigation of a

5   dynamic series of images. A 4-Dimensional orthogonal

display and an interactive display tool for 4-D

visualisation, navigation and alignment quality control

of the time-sequence of 3D image data sets is provided

according to the present invention. The tool uses the

10   orthogonal display to select a point of interest - the

seed voxel/voxel- using one of the M image data sets

volumes at a time. Once a seed voxel S is chosen,

horizontal, vertical and depth time-domain images are

created and displayed as discussed above. The selection

15   of a new point of interest (i.e. a new seed S) on any one

of the time-domain images results in the reselection,

from the time-series of image data sets, of the

appropriate image data set to be used for a concurrent

display of the image plane (P) containing the reselected

20   seed voxel, along with a consistent change in the spatial

point of focus (i.e. the seed) within the image.

Figure 3 illustrates a composite interactive image

display 30 comprising a first spatial-domain image 31

25   generated from image data items selected from a single

image data set (e.g. set number m) which represent image

voxels located in a common first plane (P) containing a

first locus 45. The interactive display generates a

composite image containing the first spatial-domain image

31 and a horizontal time-domain image 33 aligned such

5   that those voxels of the first spatial-domain image and

of the time-domain 33 image which share a common image

voxel location within the reference frame are arranged

in-line.

10   The first locus is simultaneously visually presented

within the composite image as a first locus image

overlaying each of the spatial-domain 31 (item 45) and

the time-domain 33 images (item 43) and intersecting

those image voxels of the respective images which

15   intersect the first locus in the reference frame.

The composite image contains a vertical time-domain image

35 in respect of a second locus 44 which intersects the

first locus 45 at the seed voxel, and is substantially

20   coplanar with the first locus. The first spatial-domain

image 31 and the second time-domain image 35 are aligned

such that those voxels of the first spatial-domain image

and of the second time-domain image which share a common

image voxel location within the reference frame are

25   arranged in-line. A second locus image (44, 39) of the

form of the first locus image is simultaneously presented

in each of the spatial-domain image 31 and the second

time-domain image 35.

The first locus is an image row within the first spatial-

5   domain image 31 and the second locus is an image column

perpendicular to the first predefined locus. This

provides a cross-hair effect in a locus image comprising

the first and second locus images. The cross-hairs

centre upon the seed voxel location within the first

10   spatial-domain image 31.

The composite image 30 further includes a second 32 and a

third 36 spatial-domain image each separately generated

from image data items selected from the same image data

15   set employed for the first spatial-domain image. The

image data items employed in generating the second

spatial-domain image represent image voxels located in a

common second plane which contains the first locus 45

(see item 37 of image 32).   The image data items

20   employed in generating the third spatial-domain image

represent image voxels located in a common third plane

which contains the second locus (see items 38 and 36).

Each of the second and third planes is non-parallel and

non-coplanar with the first plane P and with each other.

25

The composite image contains the second spatial-domain

image 32 and the third spatial-domain image 36 each

aligned such that those voxels of the first spatial-

domain image, the second spatial-domain image and the

5   first time-domain image which share a common voxel

location in the reference frame are arranged in-line.

Similarly, those voxels of the first spatial-domain

image, the third spatial-domain image and the second

time-domain image which share a common voxel location

10   within the reference frame are arranged in-line.

Consequently, a third spatial domain (i.e. depth) is

represented within the composite image by the presence of

the second and/or third spatial-domain images. The

second spatial-domain image shares one common spatial

15   dimension (i.e. the horizontal dimension) with both the

first spatial-domain image 31 and the first time-domain

image 33. Similarly, the third spatial-domain image

shares one common spatial dimension (i.e. the vertical

dimension) with both the first spatial-domain image 31

20   and the second time-domain image 35. A third time-domain

image 34 is provided within the composite image 30

aligned to the horizontal axis of the third spatial-

domain image 36.

25   Each image within the composite image contains a locus

image (items 37, 38, 39, 40, 41, 42, 43, 44, 45)

representing those voxels within the image which are
intersected by a locus.

Figure 3 presents the general view of a 4-Dimensional
orthogonal display according to the present invention.
The display shows three planes in orthogonal reformat of
a coronal stack of subtracted post-contrast breast
images. A vertical time-domain image 35 is displayed next
to the sagittal frame 36, and a horizontal time-domain
image 33 - below the axial frame 32. The "depth" time-
domain image 34 is displayed at the bottom right corner
of the composite image 30, and has a horizontal axis, and
locus image 40, aligned with that of the sagittal frame
36 and locus image 38. Similarly, the vertical axis of
the "depth" time-domaim image 34 is aligned with that of
the horizontal time domain image 33.

The relative positions of the separate images within the
composite image 30 are selected in such a way that
aligned axes coincide in the 4D space. The image on
display in Figure 3 is derived from an image data set
representing the first post-contrast image of the
subject. The display is focused on the central region of
the lesion. The time-domain images show a focal pattern
of enhancement (i.e. central part of the lesion that is

not enhanced on the first post-contrast image, but becomes enhanced later.)

A subtraction image is usually employed in dynamic
5   imaging of breast tissues for localisation of a lesion, and visual analysis of lesion morphology. It follows that the quality of the subtraction image is essential for the correct interpretation of the image data.

10   The present invention is effective for patient motion detection which, if left undetected, could lead to poor or erroneous image diagnosis.

The present invention provides a method and apparatus for
15   the assessment of the alignment of 3D imaged subject volumes and is suitable for detecting motion artefacts resulting from local areas of motion/ deformations within the imaged volume as well as global motion. It is of particular importance for breast imaging because of the
20   high elasticity of breast tissue which renders it susceptible to localised (non-global) movements due to deformations.

Furthermore, the present invention also provides a method
25   of visualisation of dynamic contrast enhancement in a subject. A time-domain image of subtracted post-contrast

images (or other post-processed images) will show the enhancement pattern dynamics. This allows radiologist looking at one volume at a time to use additional information from all the range of dynamic volumes. The 4D orthogonal display provides the interface for effective 'navigation' in 4D dynamic data. The tool can be used for both motion detection and visualisation. The ability to review simultaneously the subtracted image and the time-domain image of the whole range of subtraction images focused on the lesion may provide additional power to the interpretation process.

A further illustrative example is discussed below with reference to Figure 6 and Figure 7. The proposed method is based on using auxiliary 2D images that will be referred to as temporal domain linograms. A temporal domain linogram (TDL) shows a time evolution of a free form line passing through the region of interest. This line will be further referred to as a spatial locus of the TDL. A sequence of voxels taken at the specific spatial locations defined by the locus is extracted from each one of the consecutively acquired volumes. The extracted loci are aligned following the order of acquisition, thus forming a 2D image having one temporal and one spatial axis. If the volumes are properly aligned, the extracted loci will correspond to the same

spatial locations relative to the patient, and therefore should be correlated. Thus the TDL will display a pattern of bars parallel to the temporal axis. (Those bars are traces of anatomical details.) Disturbances of

5   this pattern will indicate spatial misalignment of the volumes. For example, if the locus intercepts a blood vessel, trace of the blood vessel on the TDL will be disturbed by motion having a component orthogonal to its spatial axis. The region of misalignment detected on the

10 TDL can be located by projecting it back into the original image data.

The creation and use of a temporal domain linogram (TDL) preferably follows a procedure in which the imaged volume

15 is defined by a spatial frame of reference, R, with axes L (left), P (posterior), H (cranial). The spatial locus, S, is a free form line passing through the region of interest (ROI). A sequence of voxels taken at the spatial locations defined by the locus is extracted from each one

20 of the consecutively acquired volumes. The extracted loci are aligned following the order of acquisition of the volumes. If there are no misalignments at the locations defined by the locus, the image will present a pattern of lines parallel to the temporal axis. Local

25 disturbances of the above described pattern indicate motion (i.e. misalignment of the volumes).

Figure 6 presents the general view of the proposed 4D orthogonal display. The display shows a three plane orthogonal reformat of one of the subtracted post-
5   contrast volumes of a breast dynamic image along with three TDLs. The TDLs are created using three loci of the form of straight line, intercepting in the point of focus of the orthogonal display. The loci are mutually orthogonal, and each one is parallel to one of the main
10   spatial axes of the volume. The TDLs are displayed in the way that their loci are aligned with the corresponding spatial axes of the displayed reformatted images. The interface is similar to one of a 3D orthogonal display. A point of interest may be chosen on any of the reformatted
15   images or TDLs. By choosing the point of interest on a TDL, one actually chooses a temporal point (i.e. a specific volume in the sequence) and a spatial point on the locus of the TDL. As a result, the 3D volume used for display will be consistently altered along with
20   changing the spatial point of focus. In this way the display expands on the classic 3D orthogonal display by adding the fourth, temporal, dimension.

Using the 4D orthogonal display one can navigate to the
25   region of the lesion and check this local region for motion observing the TDLs. The display also allows

tracing the misalignment detected on a TDL back to the original volume data. By varying the selected planes from the 3D volume, any region within the imaging field can be interrogated.

5

If no motion was detected at the region of interest, the TDL can be also used for 4D visualization of the pattern of contrast enhancement. This becomes possible if one creates a subtracted TDL, i.e. the TDL where the locus

10 extracted from the pre-contrast dataset is subtracted from the loci extracted from the post-contrast datasets.

Figure 6 presents a general view of 4D orthogonal display tool. The display contains three-plan orthogonal

15 reformat of a subtracted breast volume, and three TDLs. The original volume has coronal plane orientation. The loci of TDLs are mutually orthogonal straight lines. Each locus is parallel to one of the main axes of the volume. The reformat images and the loci share one common point

20 in space and time – point of focus of the display (shown by the arrow in all the views). Spatial axes of TDLs are aligned on display with the corresponded axes of the reformatted images: The Left/Right (LR) TDL (3) is aligned with LR axes of the coronal (1) and the axial (2)

25 views; Anterior/Posterior (AP) TDL (5) – with AP axis of the sagittal view (4); and Cranial/Caudal TDL (6) – with

the Cranial/Caudal axes of the coronal and sagittal views.

The temporal domain linogram method was applied to 81 dynamic studies of women at high risk of breast cancer. Informed consent of the patients was requested for use of anonymised images for research purposes. Each study consists of two pre-contrast and at least four post-contrast datasets acquired after administration of Gd-DTPA using a 3D T1-weighted fast spoiled gradient echo sequence. Temporal resolution was 90 sec. in most cases. It was found that 16 cases have no motion, 34 have prominent motion, and local motion was found in 31 cases. Three examples are presented herein.

Figure 7 shows a measurement that was assessed for motion, and in which no motion was found. The shown image is a subtracted post-contrast image acquired at 90 sec. after administration of Gd-DTPA using a Siemens 1.5T Vision scanner. The image shows a lesion in the right breast. The lesion was histologically identified as malignant (invasive mixed lobular and no specific type

(NST) carcinoma, grade II). The presented subtracted TDLs demonstrate a centripetal pattern of enhancement (i.e. the central region of the lesion enhances later than the periphery) characterizing malignant lesion.

5

Figure 7 presents subtracted temporal domain linograms, with no detected motion. The subtracted image (A) shows a lesion in the right breast. The central region of the lesion (shown by the arrow) is enhanced to smaller extent than the periphery. Subtracted TDLs (B, C) show that the central region becomes enhanced at the late post-contrast time, when the contrast material partly washed out of the peripheral regions. The TDLs' loci are straight lines intercepting in the central region of the lesion.

15

To improve visual representation all the presented TDLs are zoomed by a factor 4 in the time domain using linear interpolation. This representation may yield the optimal visual perception. Although nearest neighbour interpolation seems to accentuate misalignment details, linear interpolation smoothes differences in the intensities between volumes that helps to concentrate the attention on misalignments.

25 Subtraction images are often employed in dynamic imaging of breast for suppression of fatty tissue, to localize

lesions, and to aid in visual analysis of lesion morphology. Prominent motion can readily be identified by observing the subtraction image. However, local motion of the breast may produce an artifact that can mislead the

5   observer. Applying the proposed approach routinely for assessment of findings, one can distinguish between a motion artifact and a lesion. The method enables a fast, convenient and objective comparison of volumes, which is recommended for radiological practice as a mean of

10   validating findings and detecting 'pseudo lesions'. A TDL is easy to interpret and can be saved with the patient data for reporting. The TDL can be used to assess motion of the whole volume and validate a need for motion correction where there is no obviously observable bulk

15   motion. This can be done by examining multiple randomly selected local regions from the imaged volume.

Modifications and variants to the above embodiments, such as would be readily apparent to the skilled person, are

20   encompassed within the scope of the present invention.

25